The unusual influence of hetaryl groups on the direct conversion of some secondary alcohols into thiols with Lawesson's reagent: elucidation of the reaction mechanism

Mlostoń, Grzegorz ; Hamera-Faldyga, Roza ; Celeda, Malgorzata ; Linden, Anthony ; Heimgartner, Heinz

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The Unusual Influence of Hetaryl Groups on the Direct Conversion of Some Secondary Alcohols into Thiols with Lawesson's Reagent; Elucidation of the Reaction Mechanism

Grzegorz Mlostoń[a], Małgorzata Celeda[a], Róża Hamera-Fałdyga[a,#], Anthony Linden[b], and Heinz Heimgartner[b]

[a]Department of Organic and Applied Chemistry, University of Łódź, Łódź, Poland; [b]Department of Chemistry, University of Zurich, Zurich, Switzerland

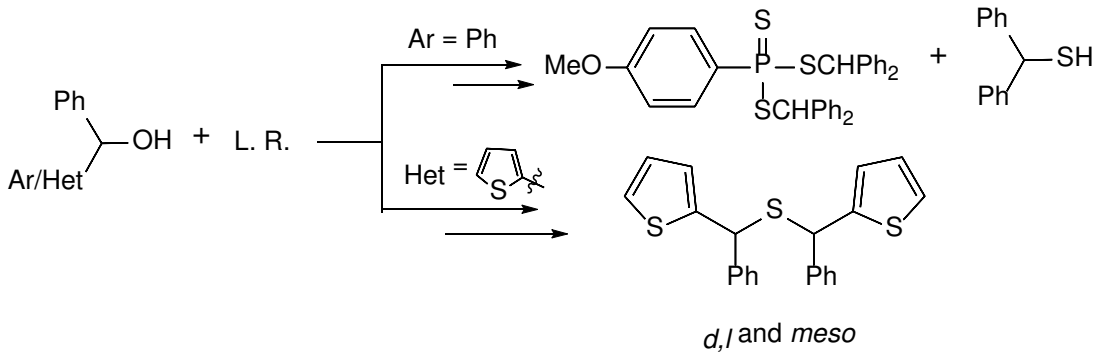
Abstract

A series of hetaryl-substituted methanols was used for direct conversion into the corresponding thiols by treatment with Lawesson's reagent in boiling toluene. Unexpectedly, the respective sulfides were formed exclusively. In the case of chiral alcohols, the sulfides were obtained as 1:1-mixtures of *meso*- and *dl*-diastereoisomers. In contrast to hetaryl-substituted alcohols, the analogous protocol applied for benzhydryl alcohol led to a mixture of the expected secondary thiol and a bis(diphenylmethyl) trithiophosphonate. Finally, the analogous reactions with ferrocenyl(phenyl)methanol and diferrocenylmethanol, respectively, led to the corresponding thiols in good yield.

CONTACT Grzegorz Mlostoń e-mail: gmloston@uni.lodz.pl address: Department of Organic and Applied Chemistry, University of Łódź, Tamka 12, PL-91-403 Łódź, Poland

[#] Part of the planned Ph.D. Thesis of R. H.-F. (University of Łódź)

Graphical Abstract



Keywords: Lawesson's reagent; secondary alcohols; secondary thiols; sulfides; hetaryl substituents

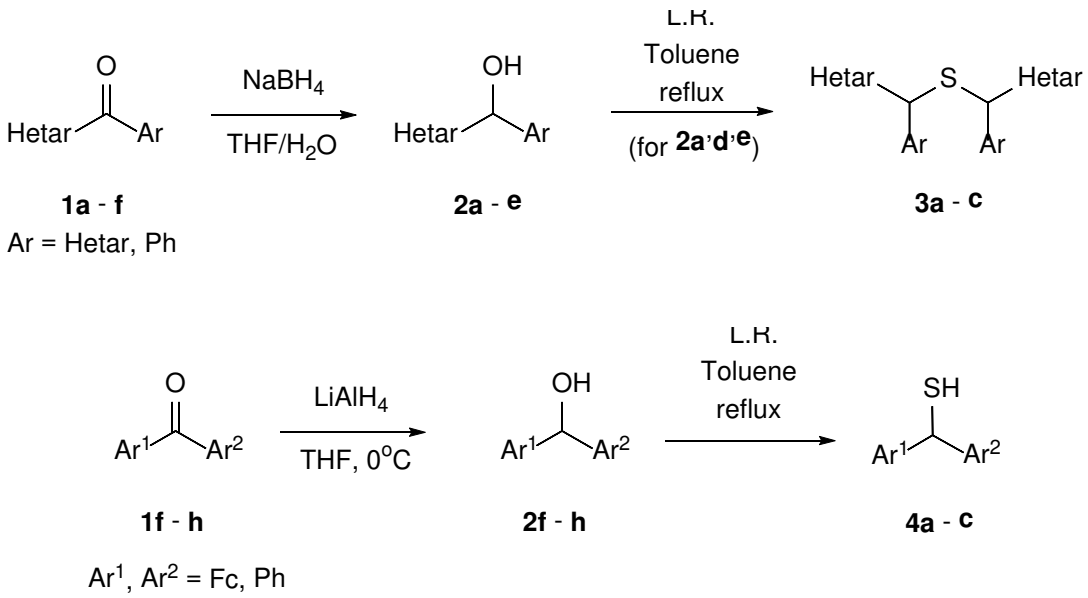
1. INTRODUCTION

Thiols are an important class of organic compounds with great significance for organic syntheses. Diverse methods are known for their preparation [1], and in recent years, asymmetric syntheses of thiols have been studied extensively [2,3]. It is well known that many thiols are biologically active substances [4] and some of them are of special interest as odorous compounds [5].

It is generally known that the treatment of primary, secondary or tertiary alcohols with Lawesson's reagent (L.R.) is a straightforward method for their conversion into the corresponding thiols [6,7]. In some recent publications, we described the synthesis of hetaryl and ferrocenyl ketones and their conversions into the sulfur analogues, i.e. thioketones [8,9]. The latter were tested as precursors of thiols by treatment with diverse reducing agents, and in the cases of aromatic and cycloaliphatic thioketones, only LDA gave satisfactory results [10]. In order to get an alternative, straightforward access to hetarylmethanethiols, the direct conversion of the corresponding secondary alcohols into the required thiols using Lawesson's reagent should be examined.

2. RESULTS AND DISCUSSION

The study started with the preparation of a series of hetaryl and ferrocenyl substituted ketones **1** via lithiated hetarenes [8] or via the in-situ-generated mixed anhydrides [9].



Scheme 1. Preparation of disubstituted methanols **2** and their transformations into sulfides **3** or thiols **4**.

The obtained ketones **1a**-**e** were converted into the corresponding secondary alcohols **2a**-**e** via reduction with $NaBH_4$ in THF solution (Scheme 1, Table 1) or alternatively, in the case of phenyl/ferrocenyl ketones **1f**-**h**, with lithium aluminum hydride. In the first thiolation experiment, di(thiophen-2-yl)methanol (**2a**) was treated with ca. equimolar amounts of L.R. in boiling absolute toluene. The progress of the reaction was monitored by TLC, and after 15 min, the starting material **2a** was completely consumed. The crude reaction mixture, after removal of toluene, was analyzed by ^{1}H NMR spectroscopy, which evidenced the formation of only one product. Along with two doublets and a triplet for the thiophene ring, the spectrum showed a singlet at 5.43 ppm. Surprisingly, the expected IR absorption band for the SH group at ca. 2500–2600 cm^{-1} was missing. The elemental analysis of the purified sample showed a significantly reduced value for sulfur in comparison with that calculated for the

desired thiol (40.99 instead of 47.09%). This value corresponded, however, to the molecular formula $C_{18}H_{14}S_5$ of the sulfide **3a**.

A similar reaction course was observed in the case of hetaryl(phenyl)methanols **2d-e** (Table 1). However, in both cases, 1:1-mixtures of two diastereoisomeric products **3b** and **3c** (*meso* and *dl*) were obtained. These mixtures could not be separated by means of standard chromatographic methods. For example, the ^{1}H NMR spectrum of sulfide **3b** showed two equally intense singlets at 5.11 and 5.12 ppm, which are attributed to the CH-S-CH fragment in the two diastereoisomers. In addition, the ^{13}C NMR spectrum revealed two signals for this fragment at 49.79 and 49.82 ppm, respectively.

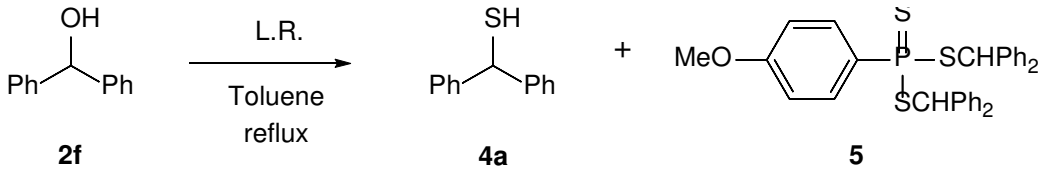
Table 1. Aryl/hetaryl and ferrocenyl substituted methanols **2**, sulfides **3**, and thiols **4**.

1	Hetar or Ar[1]	Hetar or Ar[2]	**2**	Yield (%)[a]	**3**	**4**	Yield (%)[a]
a	Thiophen-2-yl	Thiophen-2-yl	**a** [11,12]	79	**a**	-	75
b	Thiophen-2-yl	Selenophen-2-yl	**b** [12]	94	**-**	-	-[b]
c	Furan-2-yl	Selenophen-2-yl	**c**	65	**-**	-	-[b]
d	Phenyl	Thiophen-2-yl	**d** [11,12]	93	**b**	-	92
e	Phenyl	Selenophen-2-yl	**e** [13]	68	**c**	-	75
f	Phenyl	Phenyl	**f** [14]	99	**-**	**a** [6]	90
g	Ferrocenyl	Phenyl	**g** [15]	84	**-**	**b**	58
h	Ferrocenyl	Ferrocenyl	**h** [16]	89	**-**	**c**	56

[a] Yield of isolated product.
[b] Only non-identified decomposition products were obtained

The presented results differ significantly from the reported formation of diphenylmethanethiol (**4a**) from benzhydryl alcohol (**2f**) under similar conditions [6]. For that reason, the experiment with **2f** was repeated in boiling absolute toluene, and the TLC analysis showed that already after 15 min the starting material was completely consumed, and two new spots evidenced the formation of two new products. After

chromatographic separation, the less polar fraction was identified as the known diphenylmethanethiol (**4a**) [6] as the major product. The more polar fraction, obtained as the minor product, was isolated as a colorless solid, and the ^{31}P NMR spectrum indicated the presence of a P-atom by a signal at 78.2 ppm, i.e., in the region of aryltrithiophosphonates [17–20]. In the ^{1}H NMR spectrum, signals of a MeO group (3.78 ppm) and of a 4-MeOC_6H_4 residue (6.66–6.68 and 7.60–7.65 ppm) suggested the presence of a monomeric unit of Lawesson's reagent. In addition, comparison of the intensities of the MeO and the $CHPh_2$ groups (doublet at 5.79 ppm) proved the ratio 3:2 for the respective H-atoms. Based on these data, structure **5** (Scheme 2) was attributed to this product (cf. [19]). The elemental analysis supported the molecular formula $C_{33}H_{29}OPS_3$. Finally, the proposed structure was unambiguously confirmed by X-ray crystallography (Figure 1). The corresponding bis(diphenylmethyl) phenyltrithiophosphonate of type **5** has been obtained in a two-step reaction from phenylphosphine and thiobenzophenone [19].



Scheme 2. Reaction of benzhydryl alcohol (**2f**) with Lawesson's reagent (L.R.) in abs. toulene.

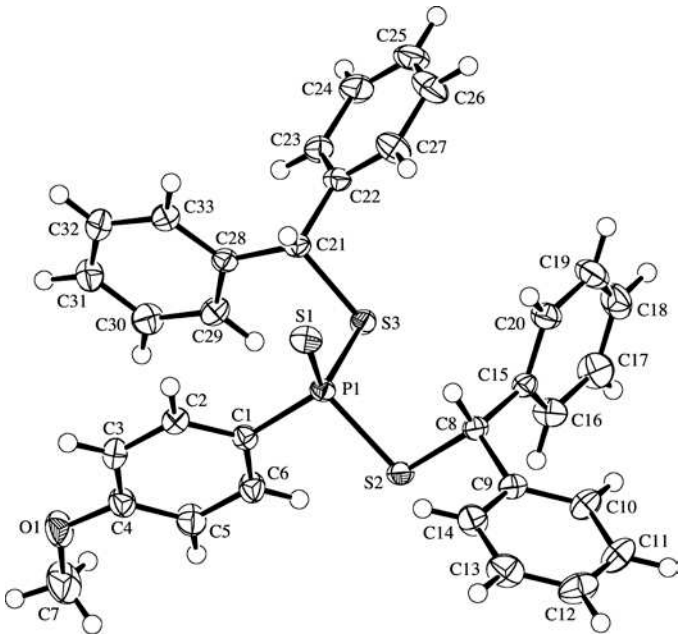
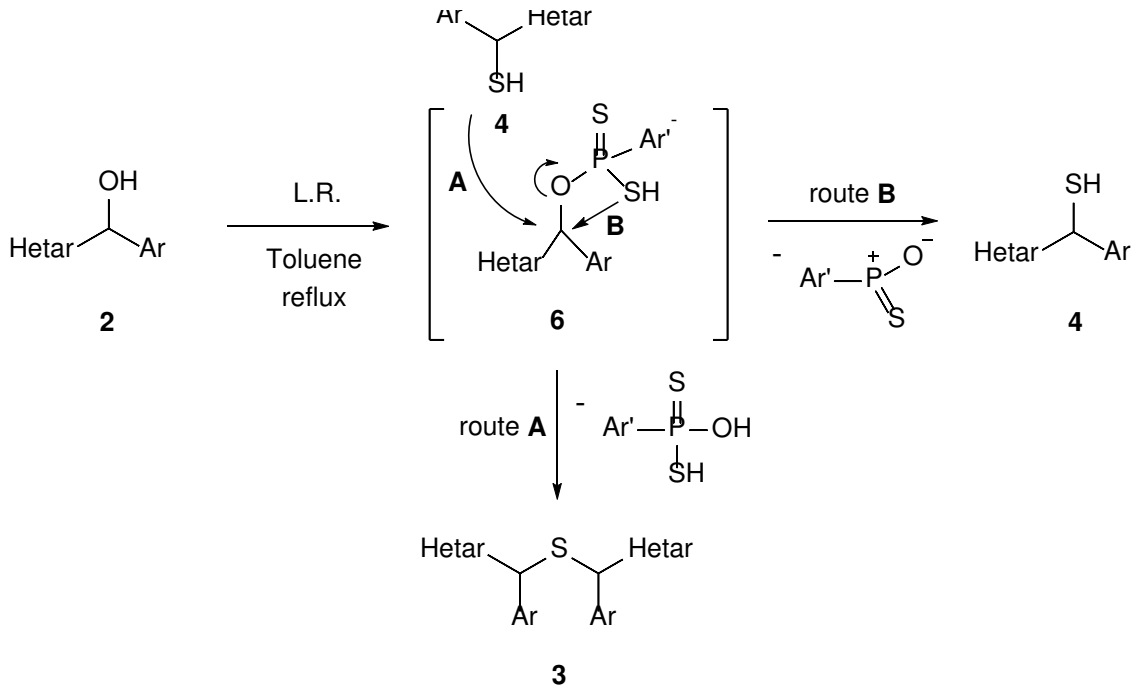


Figure 1. ORTEP plot [21] of the molecular structure of **5** (with 50% probability ellipsoids; arbitrary numbering of atoms)

The formation of product **5** or its analogues has not been reported in earlier publications [6,22] on the direct conversion of **2f** and other secondary alcohols into the corresponding thiols. As a matter of fact, in supplementary experiments performed with **2f** in wet toluene, the formation of **5** has not been observed, and thiol **4a** was isolated as the only product in good yield (90%), in agreement with the reported results. In a test experiment, the isolated compound **5** was heated in wet toluene over 0.5 h, but in this case the starting compound was recovered. Thus, thiol **4a** is not a product of hydrolysis of the initially formed **5**. In order to check whether the latter can be formed from thiol **4a** and monomeric L.R., both reagents, used in a molar ratio of 2:1 were heated in boiling toluene until **4a** completely disappeared from the reaction mixture (TLC monitoring). As a matter of fact, formation of **5** was evidenced by TLC, however, many other spots revealed a rather complicated outcome of the reaction. Based on this observation we conclude that the formation of **5** occurs via an intermediate formed in the initial step of the reaction from alcohol **2f** (and not from the in situ formed thiol **4a**), and Lawesson's reagent. The detailed mechanism of this conversion in not clear yet.

Finally, the experiment with ferrocenyl(phenyl)methanol (**2g**) led to the corresponding thiol **4b**, which was isolated in 58% yield (Scheme 1, Table 1). In the reaction mixture, non-identified decomposition products were also present, but neither a sulfide of type **3** nor an analogue of **5** could be identified. An analogous result was obtained with diferrocenylmethanol (**2h**), and in this case diferrocenylmethanethiol (**4c**) was isolated in a comparable yield (Table 1).

The results of the present study showed that the presence of a hetaryl residue in the secondary alcohols **2** changes the reactivity of the system, and instead of methanethiols of type **4**, sulfides **3** are formed as unexpected products. It seems likely that the intermediate aryl dithiophosphonate **6** is attacked by the in-situ-formed secondary thiol of type **4** to give the sulfide **3** (route **A**). Its formation suggests that the intermediate **6** acts as a trapping agent for the nucleophilic thiol **4** (Scheme 3). This interpretation leads to the conclusion that the intermolecular *S*-attack is a competitive pathway to the intramolecular one, which leads to the formation of the thiol **4** (route **B**).



Scheme 3. Proposed reaction mechanisms for the competitive formation of sulfides **3** and thiols **4**.

In the reaction with benzhydryl alcohol (**2f**) in abs. toluene, the initially formed diphenylmethanethiol (**4a**) behaves differently and reacts with the monomer of Lawesson's reagent to give, after elimination of H_2S, dibenzhydryl (4-methoxyphenyl)trithiophosphonate (**5**). However, in the presence of water **4a** is the exclusive product. A similar example of the formation of a trithiophosphonate from Lawesson's reagent and an in-situ-generated pyrazole-3-thiol has already been described [23].

3. CONCLUSIONS

In continuation of our recent studies on hetaryl-substituted organic systems, the presented results demonstrate that hetaryl groups, in comparison with aryl groups, strongly modify the reactivity of such systems. The known protocol for the direct conversion of secondary diphenyl alcohols (benzhydryl alcohols) into the corresponding thiols by treatment with Lawesson's reagent leads, in the case of hetaryl analogues, to the corresponding sulfides as final products. The initially formed thiols are trapped by an activated intermediate generated from the starting alcohol and Lawesson's reagent.

The importance of a hetaryl group is emphasized by the fact that both benzhydryl alcohol and ferrocenyl(phenyl)methanol behaved similarly, and in both cases only the respective thiols were formed. These results point out that the presence of the hetaryl groups strongly modifies the reactivity of the SH moiety, very likely by the enhancement of its nucleophilicity. It should be emphasized that in a similar study performed with ferrocenyl/hetarylmethanols of type **2** and L.R., another mechanism governs the reaction course and the formation of tetra-substituted ethane derivatives was observed [24]. All these results point out that the type of products obtained from secondary alcohols, derived from methanol, strongly depends on the substitution pattern and both hetaryl and ferrocenyl groups are of special importance.

4. EXPERIMENTAL

4.1. General

All solvents were dried over appropriate drying agents and distilled before use. Melting points were determined in a capillary using a Stewart® SMP 30 and they are uncorrected. The IR spectra were recorded on a Nexus FT-IR spectrophotometer. The ^{1}H, ^{13}C and ^{31}P NMR spectra were measured on a Bruker Avance III instrument (600, 150 and 243 MHz, respectively), using the solvent signal and H_3PO_4, respectively, as reference. The elemental analyses were recorded on a Vario Micro Cube. ESI-MS were recorded on a Varian 500-MS IT mass spectrometer. Column chromatography (CC) was carried out using Silica gel 60 (Sigma-Aldrich, 230–400 mesh). The notation Fc in this study represents the ferrocenyl residue. The applied ferrocenyl- and hetaryl-substituted ketones were obtained by known methods according to the literature protocols [8,9]. Other reagents used in the present study were commercially available.

4.2. Synthesis of secondary alcohols 2a-f

To a solution of the corresponding ketone **1** (1 mmol) in THF (2 mL), water (0.06 mL) and $NaBH_4$ (1.25 mmol, 0.047 g) were added. The mixture was heated at reflux for 2 h. Then, the solution was diluted with water (10 mL) and THF was evaporated. The residue was extracted with ethyl acetate. The combined organic layers were dried over $MgSO_4$. The solvent was evaporated and crude products were purified by CC (SiO_2, petroleum ether/ethyl acetate 8:2).

4.2.1. Di(thiophen-2-yl)methanol (2a)

Colorless solid; yield: 147 mg (79%); m.p. 50.0–52.0°C (petroleum ether/CH_2Cl_2) ([12]: m.p. 53°C). ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.76 (*d*, $^3J_{H,H}$ = 4.2 Hz, OH), 6.30 (*d*, $^3J_{H,H}$ = 4.2 Hz, CH–O), 6.99 (*dd*, $^3J_{H,H}$ = 3.6 Hz, $^3J_{H,H}$ = 4.8 Hz, $2CH_{arom}$), 7.02−7.05 (*m*, $2CH_{arom}$), 7.30 (*d*, $^3J_{H,H}$ = 4.8 Hz, $2CH_{arom}$) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ 68.5 (CH–O), 125.0, 125.4, 126.6 ($6CH_{arom}$), 147.1 ($2C_{arom}$) ppm. IR (KBr): υ 3243*s* (OH), 3101*m*, 2923*m*, 2854*m*, 2357*m*, 2027*w*, 1945*w*, 1792*w*, 1733*w*, 1673*w*, 1606*w*, 1537*w*, 1439*m*, 1363*m*, 1347*m*, 1271*m*, 1230*m*, 1163*m*, 1135*m*, 1075*m*, 1006*s*, 850*m*, 796*m*, 752*m*, 701*vs* cm^{-1}. Anal. calcd for $C_9H_8OS_2$ (196.29): C 55.07, H 4.11, S 32.67; found: C 55.25, H 4.18, S 32.51.

4.2.2. (Selenophen-2-yl)(thiophen-2-yl)methanol (2b)

Pale yellow solid; yield: 228 mg (94%); m.p. 58.0–60.0°C (petroleum ether/CH_2Cl_2) ([12]: m.p. 62.5°C). ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.74 (*d*, $^3J_{H,H}$ = 3.6 Hz, OH), 6.30 (*d*, $^3J_{H,H}$ = 3.6 Hz, CH–O), 6.97−7.01 (*m*, $1CH_{arom}$), 7.04−7.07 (*m*, $1CH_{arom}$), 7.17−7.19 (*m*, $1CH_{arom}$), 7.20−7.23 (*m*, $1CH_{arom}$), 7.30 (*dd*, $^4J_{H,H}$ = 1.2 Hz, $^3J_{H,H}$ = 5.4 Hz, $1CH_{arom}$), 7.99 (*dd*, $^4J_{H,H}$ = 1.2 Hz, $^3J_{H,H}$ = 5.4 Hz, $1CH_{arom}$) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ 70.3 (CH–O), 124.9, 125.5, 126.6, 126.9, 129.1, 130.9 ($6CH_{arom}$), 147.5, 154.6 ($2C_{arom}$) ppm. IR (KBr): υ 3500*s* (OH), 3414*s*, 3098*m*, 3069*m*, 2955*w*, 2920*w*, 2854*w*, 1815*w*, 1736*w*, 1673*w*, 1606*w*, 1543*m*, 1447*m*, 1372*m*, 1347*m*, 1292*m*, 1261*s*, 1217*s*, 1173*m*, 1125*s*, 1066*m*, 1014*m*, 986*s*, 856*m*, 834*s*, 807*m*, 755*m*, 698*vs* cm^{-1}.

4.2.3. (Furan-2-yl)(selenophen-2-yl)methanol (2c)

Isolated as thick oil turning brownish when stored at ambient conditions; yield: 148 mg (65%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.72 (*d*, $^3J_{H,H}$ = 4.8 Hz, OH), 6.07 (*d*, $^3J_{H,H}$ = 4.8 Hz, CH–O), 6.31−6.33 (*m*, $1CH_{arom}$), 6.35−6.38 (*m*, $1CH_{arom}$), 7.17–7.19 (*m*, $1CH_{arom}$), 7.20–7.24 (*m*, $1CH_{arom}$), 7.43 (*d*, $J_{H,H}$ = 1.2 Hz, $1CH_{arom}$), 8.00 (*dd*, $^4J_{H,H}$ = 0.6 Hz, $^3J_{H,H}$= 6.0 Hz, $1CH_{arom}$) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ 68.1 (CH–O), 107.2, 110.3, 127.1, 129.1, 131.0, 142.5 ($6CH_{arom}$), 151.7, 155.1 ($2C_{arom}$) ppm. IR (KBr): υ 3430*s* (OH), 3107*w*, 3050*w*, 2930*w*, 1720*s*, 1701*s*, 1502*m* , 1448*m*, 1369*m*, 1233*m*, 1144*m*, 1071*m*, 1011*m*, 986*m*, 922*m*, 805*m*, 739*s*, 691*vs* cm^{-1}. All attempts to prepare this product as an analytically pure sample were unsuccessful.

4.2.4. Phenyl(thiophen-2-yl)methanol (2d)

Pale yellow solid; yield: 177 mg (93%); m.p. 58.0–60.0°C (petroleum ether/CH_2Cl_2) ([12]: m.p. 62.5°C). ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.53−2.56 (*m*, OH), 6.03–6.07 (*m*, CH–O), 6.88−6.91 (*m*, $1CH_{arom}$), 6.94−6.98 (*m*, $1CH_{arom}$), 7.24−7.29 (*m*, $1CH_{arom}$), 7.31−7.35 (*m*, $1CH_{arom}$), 7.36−7.41 (*m*, $2CH_{arom}$), 7.43−7.49 (*m*, $2CH_{arom}$) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ 72.4 (CH–O), 124.8, 125.3, 126.3, 126.6, 127.9, 128.5 ($8CH_{arom}$), 143.1, 148.1 ($2C_{arom}$) ppm. IR (KBr): υ 3256*s* (OH), 2664*w*, 2357*m*, 2338*m*, 2145*w*, 1958*w*, 1894*w*, 1796*w*, 1768*w*, 1600*w*, 1486*m*, 1458*m*, 1435*m*, 1353*m*, 1280*m*, 1258*m*, 1201*m*, 1144*m*, 1033*m*, 1008*vs*, 916*m*, 853*m*, 824*m*, 786*m*, 726*m*, 694*vs*, 590*m*, 527*m* cm^{-1}. Anal. calcd for $C_{11}H_{10}OS$ (190.26): C 69.44, H 5.30, S 16.85; found: C 69.45, H 5.31, S 16.95.

4.2.5. Phenyl(selenophen-2-yl)methanol (2e)

Pale yellow solid; yield: 161 mg (68%); m.p. 64.0–66.0°C ([13]: m.p. 60−61°C). ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.58 (*brs*, OH), 6.04 (*brs*, CH–O), 7.04−7.08 (*m*, $1CH_{arom}$), 7.19 (*dd*, $^3J_{H,H}$ = 3.6 Hz, $^3J_{H,H}$ = 6.0 Hz, $1CH_{arom}$), 7.31−7.35 (*m*, $1CH_{arom}$), 7.37−7.41 (*m*, $2CH_{arom}$), 7.46−7.49 (*m*, $2CH_{arom}$), 7.97 (*dd*, $^4J_{H,H}$ = 1.2 Hz, $^3J_{H,H}$ = 6.0 Hz, $1CH_{arom}$) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ 74.2 (CH–O), 126.2, 126.6, 128.0, 128.5, 129.1, 130.6 ($8CH_{arom}$), 143.5, 155.8 ($2C_{arom}$) ppm. IR (KBr): υ 3215*s* (OH), 2866*m*, 2664*w*, 1958*w*, 1888*w*, 1784*w*, 1600*w*, 1587*w*, 1546*w*, 1496*m*, 1448*s*, 1328*m*, 1293*m*, 1258*m*, 1204*m*, 1195*m*, 1147*m*, 1081*m*, 1033*m*, 1021*s*, 922*w*, 821*s*, 758*m*, 707*vs*, 691*vs*, 637*m*, 580*m* cm^{-1}. Anal. calcd for $C_{11}H_{10}OSe$ (237.16): C 55.71, H 4.25; found: C 55.87, H 4.25.

4.2.6. Diphenylmethanol (benzhydryl alcohol) (2f)

Colorless solid; yield: 182 mg (99%); m.p. 62.0–63.0°C ([14]: m.p. 65–66°C). ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.37 (*d*, $^3J_{H,H}$ = 3.0 Hz, OH), 5.85 (*brs*, CH–O), 7.27−7.31 (*m*, $2CH_{arom}$), 7.33−7.38 (*m*, $4CH_{arom}$), 7.39−7.42 (*m*, $4CH_{arom}$) ppm.

4.3. Synthesis of ferrocenyl(phenyl)methanol (2g) and diferrocenylmethanol (2h)

A solution of a ferrocenyl-substituted ketone (1 mmol) in dry THF (4 mL) was placed in an ice bath, and the reducing agent $LiAlH_4$ (1.2 mmol, 0.6 mL of a 2M solution in THF) was added under an argon atmosphere. A color change from red to yellow was

observed. The reaction was monitored by TLC, and after complete reaction, a saturated aqueous solution of $MgSO_4$ (4 mL) was added. The crude mixture was filtered through Celite, the solvent was evaporated, and alcohols **2g**−**2h** were obtained as analytically pure samples.

4.3.1. Ferrocenyl(phenyl)methanol (2g)

Yellow solid; yield: 245 mg (84%); m.p. 74.2–75.9°C ([15]: m.p. 78−80°C). ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.45 (*d*, $^3J_{H,H}$ = 3.0 Hz, OH), 4.18−4.19 (*m*, $1CH_{Fc}$), 4.20−4.21 (*m*, $2CH_{Fc}$), 4.22−4.23 (*m*, $1CH_{Fc}$), 4.24 (*s*, $5CH_{Fc}$), 5.49 (*d*, $^3J_{H,H}$ = 3.0 Hz, CH–O), 7.26−7.28 (*m*, CH_{arom}), 7.32−7.36 (*m*, $2CH_{arom}$), 7.39−7.41 (*m*, $2CH_{arom}$) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ 66.0, 67.4, 68.1, 68.2, 72.0 ($4CH_{Fc}$, CH–O), 68.5 (*s*, $5CH_{Fc}$), 94.3 (C_{Fc}), 126.2, 127.4, 128.2 ($3CH_{arom}$), 143.3 (C_{arom}) ppm. IR (KBr): υ 3392*m* (OH), 3082*w*, 3053*w*, 3025*w*, 2920*w*, 2851*w*, 1492*m*, 1454*m*, 1407*m*, 1382*m*, 1363*m*, 1318*m*, 1182*m*, 1100*m*, 1043*m*, 1005*s*, 926*m*, 821*s*, 723*s*, 701*vs*, 501*s*, 479*vs* cm^{-1}. Anal. calcd for $C_{17}H_{16}OFe$ (292.15): C 69.89, H 5.52; found: C 70.01, H 5.57.

4.3.2. Diferrocenylmethanol (2h)

Yellow solid; yield: 356 mg (89%); m.p. 171−173°C (decomp.) ([16]: m.p. 174−176°C). ^{1}H NMR (600 MHz, $CDCl_3$): 2.38 (*d*, $^3J_{H,H}$ = 3.0 Hz, OH), 4.15−4.17 (*m*, $6CH_{Fc}$), 4.20 (*s*, $10CH_{Fc}$), 4.25−4.26 (*m*, $2CH_{Fc}$), 5.22 (*d*, $^3J_{H,H}$ = 3.0 Hz, CH–O) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ 66.1, 67.2, 67.6, 67.8 ($8CH_{Fc}$), 68.1 (CH–O), 68.5 (s, $10CH_{Fc}$), 93.0 (C_{Fc}) ppm. IR (KBr): υ 3458*s* (OH), 3104*m*, 3089*m*, 2925*m*, 2853*m*, 1640*m*, 1407*s*, 1319*m*, 1282*m*, 1199*m*, 1162*m*, 1103*vs*, 1046*s*, 1037*s*, 1024*s*, 1000*vs*, 910*m*, 818*vs*, 749*m*, 738*m*, 525*s*, 453*vs* cm^{-1}. Anal. calcd for $C_{21}H_{20}OFe_2$ (400.07): C 63.04, H 5.04, found: C 63.23, H 5.14.

4.4. Synthesis of sulfides 3a-c

To a solution of the corresponding alcohol (1 mmol) in toluene (5 mL), under an argon atmosphere, Lawesson's reagent (0.6 mmol, 0.24 g) was added. The mixture was heated at reflux and the reaction monitored by TLC. When the alcohol was completely consumed, the solvent was evaporated and the crude products were purified by CC (SiO_2, petroleum ether/ethyl acetate 8:2).

4.4.1. Bis[di(thiophen-2-yl)methyl]sulfide (3a)

Colorless oil; yield: 146 mg (75%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 5.19 (*brs*, 1CH–S), 5.44 (*brs*, 1CH–S), 6.78−6.87 (*m*, $2CH_{arom}$), 6.96 (*dd*, $^{3}J_{H,H}$ = 3.6 Hz, $^{3}J_{H,H}$ = 4.8 Hz, $2CH_{arom}$), 6.97−7.05 (*m*, $3CH_{arom}$), 7.07−7.10 (*m*, $1CH_{arom}$), 7.12 (*dd*, $^{4}J_{H,H}$ = 1.2 Hz, $^{3}J_{H,H}$ = 4.8 Hz, $1CH_{arom}$), 7.28 (*dd*, $^{4}J_{H,H}$ = 1.2 Hz, $^{3}J_{H,H}$ = 4.8 Hz, $2CH_{arom}$), 7.30 (*dd*, $^{4}J_{H,H}$ = 1.2 Hz, $^{3}J_{H,H}$ = 4.8 Hz, $1CH_{arom}$) ppm. $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ 45.1 (2CH–S), 125.5, 126.2, 126.6 ($12CH_{arom}$), 144.5 ($4C_{arom}$) ppm. IR (film): υ 3104*m*, 3066*m*, 2927*w*, 2854*w*, 2464*w*, 2429*w*, 2287*w*, 2151*w*, 2075*w*, 1894*w*, 1793*m*, 1730*w*, 1676*w*, 1597*m*, 1527*m*, 1432*s*, 1363*m*, 1350*m*, 1277*m*, 1236*s*, 1102*m*, 1081*m*, 1043*s*, 853*s*, 755*m*, 698*s* cm^{-1}. Anal. calcd for $C_{18}H_{14}S_5$ (390.63): C 55.34, H 3.61, S 41.04; found: C 55.07, H 3.88, S 40.99.

4.4.2. (1:1)-Mixture of meso- and d,l-bis[phenyl(thiophen-2-yl)methyl]sulfide (3b)

Pale yellow oil; yield: 174 mg (92%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 5.10 (*brs*, 1CH–S), 5.11 (*brs*, 1CH–S), 6.93−7.00 (*m*, $4CH_{arom}$), 7.26−7.28 (*m*, $2CH_{arom}$), 7.29−7.33 (*m*, $2CH_{arom}$), 7.34−7.39 (*m*, $4CH_{arom}$), 7.40−7.46 (*m*, $4CH_{arom}$) ppm. $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ 49.7, 49.8 (2CH–S), 125.2, 125.3, 125.9, 126.0, 126.6, 126.7, 127.6, 127.7, 128.2, 128.5, 128.6 ($16CH_{arom}$), 140.5, 140.6, 145.1, 145.2 ($4C_{arom}$) ppm. IR (KBr): υ 3104*m*, 3059*m*, 3025*m*, 2921*m*, 2851*m*, 1945*w*, 1879*w*, 1798*w*, 1635*w*, 1598*m*, 1493*s*, 1454*s*, 1432*m*, 1264*m*, 1230*m*, 1075*m*, 1029*m*, 853*m*, 821*m*, 698*vs*, 637*m*, 590*m*, 512*m* cm^{-1}. Anal. calcd for $C_{22}H_{18}S_3$ (378.57): C 69.80, H 4.79, S 25.41; found: C 69.69, H 4.87, S 25.40.

4.4.3. (1:1)-Mixture of meso- and d,l-bis[phenyl(selenophen-2-yl)methyl]sulfide (3c)

Colorless, viscous oil; yield: 177 mg (75%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 5.18 (*brs*, 1CH–S), 5.19 (*brs*, 1CH–S), 7.03−7.08 (*m*, $2CH_{arom}$), 7.14−7.21 (*m*, $2CH_{arom}$), 7.29−7.38 (*m*, $6CH_{arom}$), 7.40−7.46 (*m*, $4CH_{arom}$), 7.92−7.97 (*m*, $2CH_{arom}$) ppm. $^{13}C\{^{1}H\}$ NMR (150 MHz, $CDCl_3$): δ 52.2, 52.3 (2CH–S), 127.6, 127.7, 128.0, 128.1, 128.2, 128.3, 128.6, 128.7, 129.1, 130.8, 130.9 ($16CH_{arom}$), 141.0, 152.8, 152.9 ($4C_{arom}$) ppm. IR (film): υ 3060*m*, 3028*m*, 2923*m*, 1951*w*, 1888*w*, 1806*w*, 1727*w*, 1600*m*, 1540*w*, 1492*m*, 1451*s*, 1333*w*, 1261*m*, 1230*m*, 1106*m*, 1074*m*, 1030*m*, 805*m*, 739*m*, 698*vs* cm^{-1}. Anal. calcd for $C_{22}H_{18}SSe_2$ (472.36): C 55.94, H 3.84, S 6.79; found: C 55.88, H 4.12, S 7.09.

4.5. Synthesis of diphenylmethanethiol (4a)

A solution of benzhydryl alcohol (**2f**) (1 mmol, 0.18 g) in a mixture of toluene (5 mL) and water (1.4 mmol, 0.025 g) with Lawesson's reagent (2.4 mmol, 0.97 g) was heated at reflux for 30 min. Next, the toluene was evaporated under reduced pressure. The crude product was purified by CC (SiO_2, petroleum ether/ethyl acetate 9:1). Colorless oil; yield of **4a** [6]: 180 mg (90%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.29 (*d*, $^3J_{H,H}$= 4.8 Hz, SH), 5.47 (*d*, $^3J_{H,H}$= 4.8 Hz, CH–S), 7.24−7.28 (*m*, $1CH_{arom}$), 7.31−7.36 (*m*, $2CH_{arom}$), 7.42−7.46 (*m*, $2CH_{arom}$) ppm.

4.6. Synthesis of ferrocenyl(phenyl)methanethiol (4b) and diferrocenylmethanethiol (4c)

Lawesson's reagent (0.6 mmol, 0.24 g) was added to a solution of ferrocenyl-substituted methanols **2g** or **2h** (1 mmol) in toluene (5 mL) under argon and heated at reflux for 10 min. Then, the solvent was evaporated and the crude product was purified by CC (SiO_2, petroleum ether/CH_2Cl_2 7:3). Both products undergo decomposition, even when stored at −78°C (dry ice) for a longer time.

4.6.1. Ferrocenyl(phenyl)methanethiol (4b)

Thick colorless oil; yield: 179 mg (58%). ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.38 (*d*, $^3J_{H,H}$ = 4.2 Hz, SH), 4.09 (*brs*, $1CH_{Fc}$), 4.14 (*brs*, $1CH_{Fc}$), 4.18 (*s*, $5CH_{Fc}$), 4.20 (*brs*, $1CH_{Fc}$), 4.43 (*brs*, $1CH_{Fc}$), 5.17 (*d*, $^3J_{H,H}$= 4.2 Hz, CH–S), 7.20−7.24 (*m*, $1CH_{arom}$), 7.28−7.32 (*m*, $2CH_{arom}$), 7.33−7.38 (*m*, $2CH_{arom}$) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$): δ 44.1 (CH–S), 67.7, 67.8, 67.9, 68.1 ($4CH_{Fc}$), 69.0 ($5CH_{Fc}$), 91.8 (C_{Fc}), 127.1, 127.3, 128.4 (5 CH_{arom}), 144.6 (C_{arom}) ppm. IR (KBr): υ 3091*m*, 3028*m*, 2965*m*, 2923*m*, 2854*w*, 2566*w*, 1951*w*, 1875*w*, 1641*m*, 1600*m*, 1496*m*, 1451*s*, 1413*m*, 1268*m*, 1103*s*, 1027*s*, 995*m*, 821*vs*, 707*vs* cm^{-1}. Anal. calcd for $C_{17}H_{16}FeS$ (308.22): C 66.25, H 5.23, S 10.40; found: C 66.08, H 5.24, S 10.27.

4.6.2. Diferrocenylmethanethiol (4c)

Thick colorless oil; yield: 233 mg (56%). ^{1}H NMR (600 MHz, C_6D_6): δ 2.40 (*brs*, SH), 3.89–3.95 (*m*, $6CH_{Fc}$), 4.08 (*s*, $10CH_{Fc}$), 4.25 (*brs*, $2CH_{Fc}$), 4.73 (*brs*, CH–S) ppm. $^{13}C\{^1H\}$ NMR (150 MHz, C_6D_6): δ 67.4, 67.5, 67.9, 68.2 ($8CH_{Fc}$), 69.3 ($10\ CH_{Fc}$), 69.5 (CH–S), 93.7 (C_{Fc}) ppm. IR (KBr): υ 3085*m*, 2920*m*, 2847*m*, 2569*w*, 1613*m*, 1461*m*, 1410*m*, 1258*m*, 1103*s*, 1021*m*, 1002*m*, 818*s*, 479*vs* cm^{-1}. Anal. calcd for $C_{21}H_{20}Fe_2S$ (416.14): C 60.61, H 4.84, S 7.71; found: C 60.48, H 4.74, S 7.52.

4.7. Synthesis of dibenzhydryl 4-methoxyphenyltrithiophosphonate (5)

To a solution of benzhydryl alcohol (**2f**) (1 mmol, 0.18 g) in absolute toluene (5 mL), Lawesson's reagent (2.4 mmol, 0.97 g) was added, and the mixture was heated at reflux. After 15 min, the solvent was evaporated and the crude products were separated by CC (SiO_2, petroleum ether/ethyl acetate 9:1). Yield of **4a**: 122 mg (61%). **5**: Colorless solid; yield: 104 mg (18%); m.p. 109.0–110.0°C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.78 (*s*, CH_3O), 5.79 (*brs*, 1CH–S), 5.81 (*brs*, 1CH–S), 6.67−6.71 (*m*, $2CH_{arom}$), 7.09−7.16 (*m*, $6CH_{arom}$), 7.19−7.25 (*m*, $6CH_{arom}$), 7.26−7.30 (*m*, $4CH_{arom}$), 7.32−7.36 (*m*, $4CH_{arom}$), 7.61−7.68 (*m*, $2CH_{arom}$) ppm. ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$): δ 55.4 (CH_3O), 56.8, 56.9 (2CH–S), 113.4, 113.5, 127.0, 127.2, 128.2, 128.3, 128.7, 128.9, 132.8, 132.9 ($24CH_{arom}$), 140.5, 140.6, 140.8, 140.9, 162.4, 162.5 ($6C_{arom}$) ppm. ^{31}P NMR (243 MHz, $CDCl_3$): δ 78.22 ppm. IR (KBr): υ 3056*w*, 3022*w*, 2996*w*, 2873*w*, 1597*s*, 1499*m*, 1492*m*, 1451*m*, 1309*m*, 1264*s*, 1182*m*, 1100*s*, 1024*m*, 831*m*, 698*vs*, 530*s* cm^{-1}. Anal. calcd for $C_{33}H_{29}OPS_3$ (568.75): C 69.69, H 5.14, S 16.91; found: C 69.66, H 5.26, S 16.67.

4.8. Attempted reaction of diphenylmethanethiol (4a) with Lawesson's reagent

A sample of pure **4a** (190.0 mg, 1.0 mmol) and Lawesson's reagent (242.0 mg, 0.6 mmol) were dissolved in 6 mL of dry toluene and the mixture was heated at reflux. The disappearance of **4a** was monitored by TLC (SiO_2, petroleum ether/ethyl acetate 9:1), and after 15 min, no starting material (R_f = 0.70) could be detected. Formation of the expected trithiophosphonate **5** was evidenced by comparison with a pure sample (R_f = 0.40).

4.9. X-Ray Crystal Structure Determination of Compound 5 [25].

All measurements were made on *Rigaku Oxford Diffraction SuperNova* area-detector diffractometer [26] using Mo*K*α radiation (λ = 0.71073 Å) from a micro-focus X-ray source and an *Oxford Instruments Cryojet XL* cooler. The data collection and refinement parameters are given below [25] and a view of the molecule is shown in Figure 1. Data reduction was performed with *CrysAlisPro* [26]. The intensities were corrected for Lorentz and polarization effects, and an empirical absorption correction using spherical harmonics [26] was applied. Equivalent reflections were merged. The structure was

solved by dual space methods using *SHELXT-2014* [27], which revealed the positions of all non-hydrogen atoms. The non-hydrogen atoms were refined anisotropically. All of the H-atoms were placed in geometrically calculated positions and refined by using a riding model where each *H*-atom was assigned a fixed isotropic displacement parameter with a value equal to $1.2U_{eq}$ of its parent atom ($1.5U_{eq}$ for the methyl group). The refinement of the structure was carried out on F^2 by using full-matrix least-squares procedures, which minimized the function $\Sigma w(F_o^2 - F_c^2)^2$. A correction for secondary extinction was not applied. Neutral atom scattering factors for non-H-atoms were taken from ref. [28], and the scattering factors for *H*-atoms were taken from ref. [29]. Anomalous dispersion effects were included in F_c [30]; the values for f' and f'' were those of ref. [31]. The values of the mass attenuation coefficients are those of ref. [32]. All calculations were performed using the *SHELXL*-2014 program [33].

Crystal data for **5**: $C_{33}H_{29}OPS_3$, M = 568.71, crystallized from petroleum ether/CH_2Cl_2, colorless, prism, crystal dimensions 0.15 × 0.25 × 0.26 mm, triclinic, space group $P\bar{1}$, Z = 2, reflections for cell determination 21105, 2θ range for cell determination 5 – 65°, a = 10.2285(2) Å, b = 10.8866(2) Å, c = 14.7543(3) Å, α = 80.4281(18), β = 84.6407(17), γ = 62.910(2)°, V = 1442.04(6) Å^3, T = 160(1) K, D_X = 1.310 g·cm^{-3}, μ(Mo$K\alpha$) = 0.338 mm^{-1}, scan type ω, $2\theta_{(max)}$ = 64.9°, transmission factors (min; max) = 0.955; 1.000, total reflections measured 45039, symmetry independent reflections 9732, reflections with $I > 2\sigma(I)$ 8001, reflections used in refinement 9732, parameters refined 344, $R(F)$ [$I > 2\sigma(I)$ reflections] = 0.0340, $wR(F^2)$ [all data] = 0.0886 ($w = [\sigma^2(F_o^2) + (0.0357P)^2 + 0.5162P]^{-1}$, where $P = (F_o^2+2F_c^2)/3$), goodness of fit 1.042, final Δ_{max}/σ 0.002, $\Delta\rho$ (max; min) = 0.36; –0.25 e Å^{-3}.

Disclosure statement

No potential conflict of interest was reported by the authors.

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